Submillimetre observations of comets with Odin: 2001–2005*

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Abstract

The Odin satellite, launched in Feb. 2001, is equipped with a 1.1-m submillimetre telescope. Odin was used to observe the 557 GHz line of water with high spectral resolution in 12 comets between 2001 and 2005. Line shapes and spatial mapping provide information on the anisotropy of the outgassing and constraints on water excitation, enabling accurate measurements of the water production rate. Five comets were regularly observed over periods of more than one month to monitor the variation of their water outgassing rate with heliocentric distance. Observing campaigns have been generally coordinated with ground-based observations of molecular lines at Nançay, CSO or IRAM 30-m telescopes to obtain molecular abundances relative to water.

Thanks to Odin's frequency coverage, it was also possible to detect the $H_2^{18}O$ 548 GHz line, first in comet 153P/Ikeya-Zhang in April 2002 (Lecacheux et al. (2003)) and then in comets C/2002 T7 (LINEAR), C/2001 Q4 (NEAT) and C/2004 Q2 (Machholz). The $^{16}O/^{18}O$ isotopic ratio (≈ 450) is consistent with the terrestrial value. Ammonia has been searched for in three comets through its $J_K = 1_0 - 0_0$ line at 572 GHz and was tentatively detected in C/2001 Q4 and C/2002 T7. The derived abundances of NH_3 relative to water are 0.5% and 0.3%, respectively, similar to values obtained in other comets with different techniques.

Keywords: Comets, Odin, submillimeter lines, water.

1 Introduction

Water is the main constituent of the ices of cometary nuclei. The study of cometary water is thus crucial for cometary science. Measurements of water production rates allow us to determine the

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relative abundances of cometary volatiles. Several molecules can be observed in the ultraviolet, infrared and radio domains, but the opacity of the Earth's atmosphere precludes the observation of water from the ground, except for weak lines arising from highly excited rovibrational states.

The Odin satellite (Nordh et al. 2003) was launched on 20 February 2001 on a Sun synchronous polar orbit. Odin houses a radiometer with a 1.1-m primary mirror and equipped with 5 receivers at 119 GHz and covering the 486–504 GHz and 541–580 GHz bands that are in large part unobservable from the ground. Half of the time is dedicated to astronomical studies and the other half to aeronomical investigations. The main astronomical objectives are to search for O_2 and H_2O isotopologues emission in the Universe, from the Solar System to galaxies.

The first observation of the H_2O ($1_{10} - 1_{01}$) fundamental line of water at 556.936 GHz in a comet was obtained by the Submillimeter Wave Astronomical Satellite (SWAS, Neufeld et al. 2000) in 1999. Comets have been a major observing topic for Odin: the first results were reported by Lecacheux et al. (2003) and more recent observations by Hjalmarson et al. (2005). At the end of 2005, water has been detected in 11 comets with Odin and $H_2^{18}O$ and NH_3 lines were also observed. The 557 GHz water line is one the strongest cometary submillimetre lines. Its peak intensity is about 10 K in bright comets, comparable to the other brightest lines in the sky from the Orion molecular cloud (Hjalmarson et al. 2003).

2 Observations

2.1 Odin in-flight performances

Odin is well suited for comet studies: it is equipped with single side-band receivers with system temperatures of 3000–3500 K and two to three receivers can be used simultaneously (Frisk et al. 2003). When not in "eclipse period" (roughly between mid-May and mid-August when part of Odin's orbit lies in the shadow of the Earth and power is limited), Odin can run three receivers simultaneously: the first two commonly used ("555B2" and "549A1") are covering the band of the three water isotopologues ($H_2^{16}O$, $H_2^{17}O$ and $H_2^{18}O$), and a third one "572B1" can be used to observe the fundamental line of NH_3 at 572.498 GHz. Odin is equipped with three spectrometers: a low-resolution (1 MHz) wide band (1 GHz) acousto-optical spectrometer (AOS) and two high-resolution (177 kHz, reduced to 202 kHz after 2002) autocorrelators. High resolution (corresponding to $\approx$100 m s^{-1} at 557 GHz) is essential to resolve cometary lines, and particularly to study the asymmetry of the 557 GHz water line in cometary atmospheres due to its optical thickness and self-absorption in the foreground coma (cf Lecacheux et al. (2003) and Section 2.2). The Odin beam at 557 GHz is 2.2' and the main beam efficiency is about 0.85.

Astronomical observations are usually divided into periods of about 60 min of pointing on the target per 96 min orbit. Achieving good pointing has been an area of concern with Odin. The first comet observed (C/2001 A2 (LINEAR)) was actually a bright line source used to calibrate the pointing of the satellite. The goal was to measure precisely the offset between the telescope axis and the reference of the satellite. The pointing has been then regularly checked on bright sources like the compact Orion-KL H_2O outflow and the Jupiter continuum (Frisk et al. 2003). The offset between the actual pointing and the telescope beam direction, estimated from the reconstructed attitude of the spacecraft, is now below 20". When two star-trackers are operational the pointing accuracy can be better than 5", but typically at the beginning or the end of an orbit, for $\sim$10 min, pointing and attitude reconstruction rely on only one star-tracker and here the pointing error can be as large as 1', as verified by our mapping of some bright comets. Finally the three receivers, especially the "555B2" and "549A1" used for $H_2^{16}O$ and $H_2^{18}O$ observations, are slightly misaligned, by 15" at most.

Since 28.6 April 2003, i.e. the last orbit of comet 153P/Ikeya-Zhang observations, the Odin observing mode of continuous tracking for moving targets is used for all comet observations.

During the first two years, the standard comet observing mode was simply based on a fixed pointing with coordinates updated regularly. This was done every 5–15 min, during which the comet was slightly drifting through the Odin beam because of its proper motion.

For all comet observations, data have been reduced using the reconstructed attitude and latest orbital elements in order to compute positional offsets, and make proper summations. A few observations (concerning C/2000 WM_1 and C/2001 Q4) have been affected by pointing errors of up to 60" due to the lack of precision of the ephemerides at the time of the observations, but the loss of signal had little consequences. Finally, the choice of targets and viewing opportunities are limited by the solar elongation constraint of Odin: 60° to 120°.

2.2 Comets observed with Odin

We choose to mainly target the comets that were potentially active enough for in-depth chemical investigations from ground-based and space observatories. Several comets came close enough to the Earth ($\leq$0.4 AU) with a large enough outgassing rate to undertake more detailed studies (Sections 3–6). The first four comets observed have been briefly presented in Lecacheux et al. (2003). The detailed log of all observations and their analysis will be presented in a future paper. When possible, the Odin observations were coordinated with other radio observations: with OH observations at 18 cm with the Nançay radio telescope for the long-term monitoring of the water production rate and for assessing water and OH modelling (Colom et al. 2004); with millimetre and submillimetre molecular observations with the Caltech Submillimeter Observatory (CSO) 10-m and the Institut de Radioastronomie Millimétrique (IRAM) 30-m observatories (Biver et al. 2006a), to obtain molecular abundances relative to water.

[Figure 1]

2.2.1 C/2001 A2 (LINEAR)

Comet C/2001 A2 (LINEAR) was initially a faint comet that underwent a large brightness outburst (5 magnitudes) around 28 March 2001. It then kept a sustained activity for the following months and was extensively investigated from the ground (Biver et al. 2006a). On 27 April, 3 months after launch, Odin made one of its first astronomical observations towards this comet: the spectrum corresponding to the 26 min of good pointing (within 40") is shown in Fig. 1. Perihelion took place on 24 May 2001 at 0.78 AU. The comet was then extensively mapped between 20 June and 9 July around the time when it was the closest to the Earth at 0.24 AU. 18 maps of 25-point grids 4 × 4' or 2 × 2' were planned using 90 Odin orbits. On 27 April, pointing was still in early commissioning phase and only 43 min integration out of 3 orbits yielded a detection of the comet. Before 28 June, Odin timing was wrong and only about 10% of data were useful. Between 28 June and 9 July, still only 60% of the orbits were correctly pointed to map the comet, but data were good enough to provide valuable information on the telescope pointing.

2.3 19P/Borrelly

This comet was observed shortly after the end of commissioning of Odin, which still resulted in some mispointed orbits. This 6.8-year periodic comet returned to perihelion on 15 September 2001 at 1.36 AU and was flown over by Deep Space 1 on the 21st of September. Data and results have been presented in detail in Bockelée-Morvan et al. (2004).

2.4 C/2000 WM_1 (LINEAR)

This new Oort comet had its perigee on 2 December 2001 at 0.32 AU. Perihelion took place on 23 January 2002 at 0.56 AU but it was then more difficult to observe, being further away from the Earth and too close to the Sun for Odin (elongation 30° to 60° between 24 December 2001 and 11 March 2002). The first Odin observations took place on 7 and 8 December. Observations at CSO were performed nearly in parallel, from 3 to 8 Dec. (Biver et al. 2006a). The second set of data was obtained on 12 March 2002. Ephemerides were off by 60" at the time of December observations, but maps were obtained and the signal was strong enough to detect the water line. The comet had a large outburst at the end of January that was followed by a sustained activity. Pre/post perihelion asymmetry in water production rate is suggested from the Odin observations (Table 1).

2.5 153P/Ikeya-Zhang

Comet 153P/2002 C1 (Ikeya-Zhang), discovered in February 2002, was found to be the return of the comet observed by Hevelius in 1661. It reached perihelion on 18 March 2002 at 0.51 AU and was an easy naked eye comet. Its peak total outgassing rate neared 10^{30} molec. s^{-1} . Perigee took place on 29 April 2002 at 0.40 AU. The comet was extensively studied at radio wavelengths during the March–May period (Biver et al. 2006a). Most results of the Odin observations, including the detection of $H_2^{18}O$, were presented in Lecacheux et al. (2003). Daily production rates are given in Table 1. The observed and simulated radial evolution of the H_2O line are illustrated in Fig. 2.

[Figure 2]

2.6 C/2002 X5 (Kudo-Fujikawa)

This comet passed its perihelion at only 0.19 AU from the Sun on 28 January 2003. Its water outgassing rate probably exceeded 10^{30} molec. s^{-1} at that time (Povich et al. 2003). Solar elongation constraints prevented Odin observations before 2 March 2003. Odin monitored the rapid decrease of its activity while receding from the Sun. IRAM 30-m observations were done in parallel on the 12th of March 2003 (Biver et al. 2003). The spectra are shown in Fig. 3 and show the rapid decrease of the line width and consequently coma expansion velocity. Production rates are given in Table 1 and suggest a rapid fall-off of the outgassing rate with increasing heliocentric distance (r_h) in $r_h^{-3.6}$.

[Figure 3]

2.7 29P/Schwassmann-Wachmann 1

A deep integration on the H_2O line was done on this unusual distant comet in June 2003. Parallel observations of CO (26–29 June 2003) were obtained at IRAM-30m (Gunnarsson et al. 2004). The comet had an outburst a few days before, around 14 June 2003 at $m_1 \approx 12$ but was back to $m_1 \approx 13.5$ at the time of Odin observations. A marginal detection of H_2O was possibly obtained during the first series of orbits, but not confirmed later. Could this have been due to some residual outgassing of grains released by the earlier outburst and that were dissipating? The inferred outgassing is below or comparable to that of CO ($Q_{CO} = 4 \times 10^{28}$ molec. s^{-1}) – assuming the same outgassing pattern from the nucleus and the same gas temperature (10 K).

2.8 2P/Encke

Odin observed comet 2P/Encke at its favourable passage in November 2003, when it came within 0.19 AU from the Earth. 2P/Encke is the comet known to have the shortest orbital period (3.3 years) and was then at its 59th observed return. The outgassing rate was one of the smallest measured in a comet with Odin ($5-8\times10^{27}$ molec. s^{-1}), which yielded limited signal-to-noise ratio in the maps. Fig. 1 shows the spectrum obtained on 23 November 2003 from the average of mapping points within a 2×2' box centred on the Odin beam. Ground-based observations were conducted in parallel to Odin observations (at CSO on the 16th and at IRAM 30-m on the 23rd, Biver et al. 2004).

2.9 C/2001 Q4 (NEAT)

This dynamically new Oort cloud comet came to perihelion on 16 May 2004 at 0.96 AU. It was the brightest comet of 2004 and reached a visual magnitude of $m_1 = 3.3$ in early May 2004. It has been extensively studied from the ground, especially starting in May 2004 since earlier it was a southern object. Odin monitored its outgassing rate in advance of these observing campaigns (Lecacheux et al. 2004). This comet was bright enough to motivate searches of water isotopologues and ammonia around perigee (0.34 AU on 7 May) and to map the water emission. The $H_2^{18}O$ line was detected with a signal-to-noise ratio of 13 and is shown in Fig. 4 together with the $H_2^{16}O$ line which was simultaneously observed with the AOS. The detection of NH_3 obtained at the same time with the third receiver is shown in Fig. 7. Fig. 9 shows a plot of the intensity distribution of the water line on 16 May.

[Figure 4]

2.10 C/2002 T7 (LINEAR)

Comet C/2002 T7 (LINEAR) was the second bright comet of 2004, and also the target of an extensive ground-based observing campaign (with CSO, IRAM and many other facilities, Crovisier et al. 2005, Hatchell et al. 2005, DiSanti et al. 2004). A first distant perigee (1.56 AU) took place in the autumn of 2003 when the comet was first detected in the radio (Crovisier et al. 2005). The comet was easily detected with Odin at the end of January 2004 (Table 1), still over 1.5 AU from the Sun. C/2002 T7 passed perihelion on 30 April 2004 at 0.62 AU from the Sun. Its activity dropped relatively rapidly after it reached perigee at 0.27 AU on 19 May 2004 but it was still bright enough to schedule Odin observations at the end of May, with searches of the two water isotopologues and ammonia: Fig. 5 shows the averages of the $H_2^{18}O$ and $H_2^{16}O$ lines observed between 24 and 27 May 2005 and Fig. 8 shows the ammonia line detected in parallel with a signal-to-noise ratio of 5.

[Figure 5]

2.11 C/2003 K4 (LINEAR)

This comet was more active than anticipated when detected with the Nançay radio telescope in June 2004 with $Q_{\rm OH} > 10^{29}$ molec. s^{-1} . Odin observations were scheduled post-perihelion and took the relay of the Nançay monitoring of the water outgassing. Due to a signal stronger than anticipated, the Odin monitoring was extended to February 2005 and provided the most distant confirmed detection of the H_2O 557 GHz line in a comet, at 2.2 AU from the Sun, as shown in Fig. 1. The line recorded at $r_h = 2.2$ AU is narrower ($FWHM = 0.95 \pm 0.08$ km s^{-1}) than the others (e.g. 2P/Encke and 9P/Tempel 1 which had a lower production rate though but were closer to the Sun), showing the decrease of expansion velocity with heliocentric distance. Fig. 10 shows that we may have put into evidence the turn-off of the water outgassing of the comet beyond 2 AU, where a more rapid fall-off of the outgassing is clearly visible.

2.12 C/2004 Q2 (Machholz)

This long-period comet passed perihelion (1.21 AU) and perigee (0.35 AU) in January 2005. This was the fourth naked eye comet seen in less than a year and again a very promising observing target for ground-based radio investigations and for Odin. IRAM 30-m observations were conducted on 14–18 January (Crovisier et al. 2005), at very close times to Odin ones (18–22 January), and provide a precise estimate of the gas temperature (65 ± 3 K) from the observation of over 20 methanol lines. $H_2^{16}O$ and $H_2^{18}O$ were clearly detected with Odin (Fig. 6). Ammonia was searched for in parallel with the AOS only, as the wide band is necessary to monitor the slow drift in frequency of the "572B1" receiver, via periodic observation of a telluric ozone line. Following an unexpected shut-down probably due to a solar event, the AOS had to be switched off during a little more than half of the planned NH_3 observations.

[Figure 6]

2.13 9P/Tempel 1

Observing this comet in support to the Deep Impact mission (Meech et al. 2005) was a major objective of Odin in 2005. This comet returned to perihelion on 5 July 2005 at 1.50 AU, the day after it was hit by the Deep Impact impactor (A'Hearn et al. 2005). It is a 5.5-year orbital period comet belonging to the Jupiter-family group of comets like 19P/Borrelly. 95 Odin orbits were dedicated to the monitoring of 9P/Tempel 1 water outgassing rate between 18 June and 8 August 2005 (Biver et al. 2005). The data and results will be presented in a dedicated paper (Biver et al. 2006b).

3 Comet maps

Nine point maps, with typically 1' spacing, have been acquired on most comets in order to determine the position of the true centre of brightness. The offset with respect to the expected position was generally less than 20" and due to the limited accuracy of the telescope pointing (Section 2). Wider maps (7×7' or more) have been obtained on bright comets C/2001 A2, C/2000 WM_1, 153P Lecacheux et al. (2003) and C/2001 Q4 (Fig. 9).

Mapping the H_2O emission in cometary comae provides useful constraints for an accurate determination of the water production rate. Indeed, the changes in intensity and velocity shift of the line with offset constrain the water excitation mechanism and line optical thickness. As a first step to analyze extended maps with our model (Section 4), we made radial averages of the signal and found a relatively good match of the evolution of line intensity and Doppler shift with distance to the nucleus, as illustrated in Fig. 2.

In addition, such maps aimed at providing information on the anisotropy of the outgassing. Some asymmetry was observed in the H_2O maps obtained for comet 19P/Borrelly (Bockelée-Morvan et al. 2004). Asymmetric maps were expected for comets 2P and 9P based on previous perihelion observations, but the signal-to-noise ratio was not high enough to retrieve significant information. Asymmetry seems marginally present in the extended maps of C/2000 WM_1 and C/2001 Q4, as seen in Fig. 9.

[Figure 9]

4 Water production rates

Line intensities have been converted into production rates (Table 1). A Haser model with symmetric outgassing and constant radial expansion velocity is used to describe the density, as in our previous studies (e.g. Biver et al. 1999). The water photodissociation lifetime has been evaluated from the daily solar activity (Crovisier 1989). The expansion velocity v_{exp} was generally inferred from the H_2O line shape (computation of line profiles predicts a half width at half maximum intensity on the red-shifted side about 0.1 km s^{-1} larger than v_{exp}), or from other contemporaneous observations of radio lines from CSO or IRAM 30-m.

Excitation of the water molecule rotational levels takes into account collisions with neutrals at a constant gas temperature based on ground-based measurements from other radio lines (e.g. Biver et al. 2006a) obtained nearly at the same time. Collisions with electrons also play a major role and are modelled according to Biver (1997) and Biver et al. (1999) with an electron density factor x_{ne} set to 0.2 for all data. The corresponding electron density was found to provide the best match to the radial evolution of line intensities observed in extended maps, as illustrated in Fig. 2. The optical thickness of the water rotational lines is taken into account into the excitation process using the Sobolev "escape probability" method (Bockelée-Morvan 1987).

Radiation transfer takes into account line optical thickness. The code can simulate line profiles that are generally in good agreement with observed lines (e.g. Fig. 2), when the departure from isotropic outgassing is small. It is used to convert the line intensities into the water production rates, assuming isotropic outgassing. An ortho-to-para ratio (OPR) of 3 has been assumed. Values of the OPR down to 2.4 (Crovisier et al. 1997) have been observed but would only imply an underestimate of 6% of the production rates given here. In the case of isotropic outgassing, the modelling predicts a red-shift of the line due to self-absorption in the foreground. For the strongest line observed with peak intensities around 10 K, the Doppler shift predicted ($\sim +0.26$ km s^{-1}) is somewhat lower than observed (+0.28 km s^{-1}on average), suggesting that the opacity of the 557 GHz line, and so $Q_{\mathrm{H_2O}}$, may be slightly underestimated.

Evidence of anisotropy in the outgassing, often enhanced towards the Sun, have been observed in several comets. Blue-shifted optically thin lines ($H_2^{18}O$, or HCN, CS, CH_3OH... from ground-based observations) are not uncommon. This is the case for comets C/2000 WM$_1$ (Biver et al. 2006a), 19P (Bockelée-Morvan et al. 2004), and C/2002 X5 around 12 March 2003, for which the optically thick water line at 557 GHz appears less red-shifted than expected. For C/2001 Q4 around 26 April to 2 May 2004 and C/2002 T7 between 24 and 28 May 2004, we do not have simultaneous IRAM or CSO observations, but the $H_2^{18}O$ line is blue-shifted and the red-shift of the $H_2^{16}O$ is small, so that anisotropic outgassing is likely.

If the outgassing rate is higher in the hemisphere facing the observer, then the total water production rate is likely underestimated: self-absorption responsible for the normal red-shift of the line is strongly auto absorbing the emission from the hemisphere facing the observer so that increase of outgassing on this side will not increase much the emission. For example, in the case of C/2002 T7 on 26 May 2004, assuming that the outgassing takes place only on the observer facing hemisphere leads to $Q_{\mathrm{H_2O}} = 32 \times 10^{28}$ molec. s^{-1} and a Doppler shift $\delta v = -0.07$ km s^{-1}. The isotropic assumption yields $Q_{\mathrm{H_2O}} = 22 \times 10^{28}$ molec. s^{-1} (for the same line intensity) and $\delta v = +0.25$ km s^{-1}: the observed Doppler shift ($\delta v = 0.0$ km s^{-1}) is closer to the value expected for the asymmetric hypothesis. Hence, production rates from Table 1 must be used with caution, especially when anisotropic outgassing is suspected.

[Figure 10]

5 Observations of the $H_2^{18}O$ isotopologue

$H_2^{18}O$ was first observed in comet 1P/Halley via mass spectroscopy (Balsiger et al. 1995, Eberhardt et al. 1995). Its first remote spectroscopic detection was obtained with Odin on comet 153P/Ikeya-Zhang in 2003 (Lecacheux et al. 2003). The $J_{Ka,Kc} = 1_{10} - 1_{01}$ transition at 547.676 GHz has been since then securely detected in C/2001 Q4 (NEAT) (Fig. 4), C/2002 T7 (LINEAR) (Fig. 5) and C/2004 Q2 (Machholz) (Fig. 6). From these spectra, we can readily see the difference between the optically thin line of $H_2^{18}O$ and the optically thick $H_2^{16}O$ line. Actually, the difference in velocity shifts of the lines is about 0.3 km s^{-1} in all cases.

The $^{16}O/^{18}O$ isotopic ratios in cometary water can be estimated from the $Q_{H_2^{16}O}/Q_{H_2^{18}O}$ ratio. The following values are measured:

- Comet 153P: $^{16}O/^{18}O = 530 \pm 60$ (Revised from Lecacheux et al. 2003);
- Comet C/2001 Q4: $^{16}O/^{18}O \approx 530 \pm 60$
- Comet C/2002 T7: $^{16}O/^{18}O \approx 550 \pm 75$
- Comet C/2004 Q2: $^{16}O/^{18}O = 508 \pm 33$

In the case of C/2001 Q4 and C/2002 T7 the $H_2^{16}O$ production rates from Table 1 have been multiplied by 1.1 and 1.2 to compensate the underestimation of Q_{H_2O} due to the non isotropic outgassing (cf. Section 4).

The case for the oxygen isotopic ratios in the Solar System is a debated problem. The terrestrial value (SMOW) for $^{16}O/^{18}O$ is 499. Indeed, in primitive bodies such as carbonaceous chondrites, most refractory inclusions show moderate anomalies in the $^{17}O/^{16}O$ and $^{18}O/^{16}O$ ratios ($\delta^{18}O = ((^{18}O/^{16}O)/(^{18}O/^{16}O)_{SMOW}\text{-}1) = -50$ to 0 $^0\!/_{00}$, Krot et al. 2005). Models of the pre-solar nebulae predict enrichments of ^{18}O in cometary water up to $\delta^{18}O = 200$ $^0\!/_{00}$ (e.g., Yin 2004)

Our measurements in four comets (≈ 520) are consistent with the terrestrial $^{16}O/^{18}O$ ratio. But imperfection in the modelling of the $H_2^{16}O$ line makes the determination of the $^{16}O/^{18}O$ ratio to be possibly slightly underestimated (Section 4).

6 Observations of ammonia

Due to the short NH_3 photodissociative lifetime (6700 s at 1 AU from the Sun), ammonia emission comes from the inner part of the atmosphere and requires a comet close to the Earth to be more easily detected. Several opportunities happened during Odin life and the $J_K = 1_0 - 0_0$ ammonia line at 572.498 GHz has been searched for in comets C/2001 Q4, C/2002 T7 and C/2004 Q2, which all came within 0.4 AU to the Earth. Unfortunately, the phase lock of the "572B1" receiver did not work before 2003 and in 2005 when we attempted to search for NH_3 in comet C/2004 Q2 (Machholz). It makes data reduction difficult as the frequency of the receiver slightly drifts with time and every spectrum needs to be carefully frequency calibrated before addition. This is especially necessary for a narrow comet line. Data obtained on comet C/2004 Q2 have not yet been reduced. NH_3 was marginally detected in comets C/2001 Q4 and C/2002 T7 (Figs. 7, 8) with line areas of $\int T_{mb} dv = 0.14 \pm 0.02$ K km s^{-1} and 0.12 ± 0.02 K km s^{-1}, respectively. Other ammonia lines are observable in the radio at 24 GHz, from the ground (e.g., Hatchell et al. 2005), but they are weaker and also suffer from beam dilution.

Production rates, assuming thermal equilibrium, are given in Table 1 and abundances relative to water are:

- C/2001 Q4: $NH_3/H_2O = 0.50 \pm 0.09\%$ ($Q_{H_2O} = 28 \pm 3 \times 10^{28}$)
- C/2002 T7: $NH_3/H_2O = 0.33 \pm 0.08\%$ ($Q_{H_2O} = 26 \pm 3 \times 10^{28}$)

Derived abundances are similar to values measured in other comets from direct observations of ammonia (Bird et al. 1999) or via observation of the NH_2 radical in the visible ($\sim$ 0.5%, Kawakita and Watanabe 2002). They are also consistent with the upper limits obtained in the same comets, from observations of the 24 GHz lines (Hatchell et al. 2005).

[Figure 7, 8]

7 Conclusion

In this paper, we presented preliminary results obtained on water and ammonia in comets using Odin:

- Velocity resolved profiles of the optically thick 557 GHz line were obtained: H_2O self-absorption is observed and manifests itself as a red-shift of the line which varies throughout the coma.
- Variations of the gas expansion velocity with heliocentric distance and outgassing rate have been measured from the line widths.
- H_2O production rates were measured. Though state-of-the-art excitation and radiative transfer models are used, some uncertainties in production rate determinations (up to 50%) remain due to the assumption of isotropic outgassing.
- The evolution of the water production rate with time and heliocentric distance has been monitored in several comets.
- The $H_2^{18}O$ 547 GHz line was detected in four comets. Comparing $H_2^{18}O$ optically thin and $H_2^{16}O$ optically thick lines provides constraints on the radiation transfer in the water dominated coma.
- With our current modelling of the $H_2^{16}O$ line, we deduce a $^{16}O/^{18}O$ ratio around 520, compatible with, although marginally higher than, the terrestrial value.
- Ammonia was detected at 572 GHz in two comets with abundance ratios ($\sim$0.4%) similar to those measured in other comets.

The current data set contains a wealth of information that will be used in the near future to improve the modelling of the excitation of water in cometary comae. Detailed modelling, including anisotropic outgassing, is one of the next necessary steps to retrieve accurate water production rates and explain the observed velocity shift of the water lines.

In the near future the Herschel Space Observatory with its HIFI heterodyne instrument will allow to observe the full submillimetre spectrum of cometary water with high sensitivity and spatial resolution (Crovisier 2005). The MIRO experiment on board the Rosetta spacecraft (Gulkis et al. 2006) will observe in situ the same lines of H_2O isotopes and NH_3 in the coma of comet 67P/Churyumov-Gerasimenko and provide detailed spatial information.

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Table 1: Cometary molecular production rates

Comet	Mean UT date [yyyy/mm/dd.d]	$< r_h >$ [AU]	$< \Delta >$ [AU]	Q_{H_2O} [10^{28} molec. s^{-1}]	$Q_{H_2^{18}O}$ [10^{26} molec. s^{-1}]	Q_{NH_3}
C/2001 A2 (LINEAR)	2001/04/27.3	0.938	0.826	10.5 ± 1.3		
	2001/06/20.8	0.937	0.278	13.4 ± 1.4		
	2001/06/21.7	0.947	0.273	11.2 ± 1.2		
	2001/06/24.5	0.977	0.258	8.9 ± 0.7		
	2001/06/26.2	0.997	0.251	10.6 ± 2.3		
	2001/06/28.4	1.023	0.245	9.7 ± 1.3		
	2001/06/30.4	1.047	0.244	6.9 ± 1.0		
	2001/07/01.8	1.062	0.244	5.7 ± 0.8		
	2001/07/02.5	1.072	0.245	5.4 ± 0.7		
	2001/07/03.0	1.078	0.246	6.0 ± 0.9		
	2001/07/06.1	1.117	0.256	5.3 ± 0.8		
	2001/07/07.6	1.135	0.264	4.7 ± 0.4		
	2001/07/09.3	1.157	0.273	4.2 ± 0.7		
19P/Borrelly	2001/09/23.4	1.362	1.472	3.8 ± 0.5		
	2001/11/05.5	1.483	1.340	2.6 ± 0.4		
C/2000 WM$_1$ (LINEAR)	2001/12/07.9	1.117	0.339	5.0 ± 0.8		
	2002/03/12.6	1.170	1.238	6.7 ± 0.5		
153P/2002 C1	2002/04/22.2	0.919	0.419	33.4 ± 1.4		
(Ikeya-Zhang)	2002/04/24.6	0.961	0.415	23.6 ± 1.5		
	2002/04/27.1	0.997	0.407	21.5 ± 0.8	4.2 ± 0.3	
	2002/04/28.2	1.022	0.405	19.1 ± 1.2		
C/2002 X5	2003/03/03.4	0.987	0.934	3.2 ± 0.2		
(Kudo-Fujikawa)	2003/03/12.5	1.178	1.092	2.1 ± 0.2		
	2003/03/21.7	1.361	1.304	1.1 ± 0.2		
	2003/03/30.6	1.529	1.540	0.8 ± 0.3		
29P/Schwassmann-W. 1	2003/06/26.5	5.752	5.305	< 2.5		
2P/Encke	2003/11/16.7	1.014	0.261	0.49 ± 0.07		
	2003/11/23.7	0.896	0.275	0.78 ± 0.16		
C/2001 Q4 (NEAT)	2004/03/06.6	1.518	1.734	17.1 ± 0.4		
	2004/03/15.6	1.413	1.534	16.3 ± 0.7		
	2004/03/24.6	1.311	1.319	17.4 ± 1.0		
	2004/04/02.6	1.216	1.087	20.0 ± 1.4		
	2004/04/13.6	1.113	0.790	26.0 ± 4.0		
	2004/04/29.8	1.000	0.383	$^a25.4 \pm 1.7$	5.3 ± 0.4	14.1 ± 2.1
	2004/05/16.0	0.962	0.436	22.2 ± 2.9		
C/2002 T7 (LINEAR)	2004/01/26.6	1.757	1.860	32.4 ± 1.1		
	2004/02/01.7	1.666	1.910	28.0 ± 0.9		
	2004/05/25.9	0.931	0.407	$^a21.8 \pm 2.3$	4.7 ± 0.4	8.7 ± 1.7
	2004/05/29.2	0.973	0.488	19.2 ± 2.9	2.5 ± 0.7	
C/2003 K4 (LINEAR)	2004/11/27.7	1.269	1.395	21.8 ± 1.5		
	2004/12/15.6	1.453	1.181	17.0 ± 0.3		
	2004/12/28.7	1.601	1.164	14.5 ± 0.6		
	2005/01/05.7	1.694	1.229	12.8 ± 0.9		
	2005/01/17.7	1.836	1.419	11.7 ± 0.4		
	2005/02/04.7	2.053	1.842	6.6 ± 0.5		
	2005/02/19.7	2.233	2.247	3.8 ± 0.4		
C/2004 Q2 (Machholz)	2005/01/20.0	1.208	0.396	26.4 ± 0.8	5.2 ± 0.2	
9P/Tempel 1	2005/06/18.2	1.516	0.818	1.15 ± 0.10		
	2005/06/23.7	1.511	0.842	1.24 ± 0.13		

[a]: Value probably underestimated by about 10–20% due to asymmetric outgassing (see text). The uncertainty on the production rate takes into account dispersion from values determined from different offset points when available.

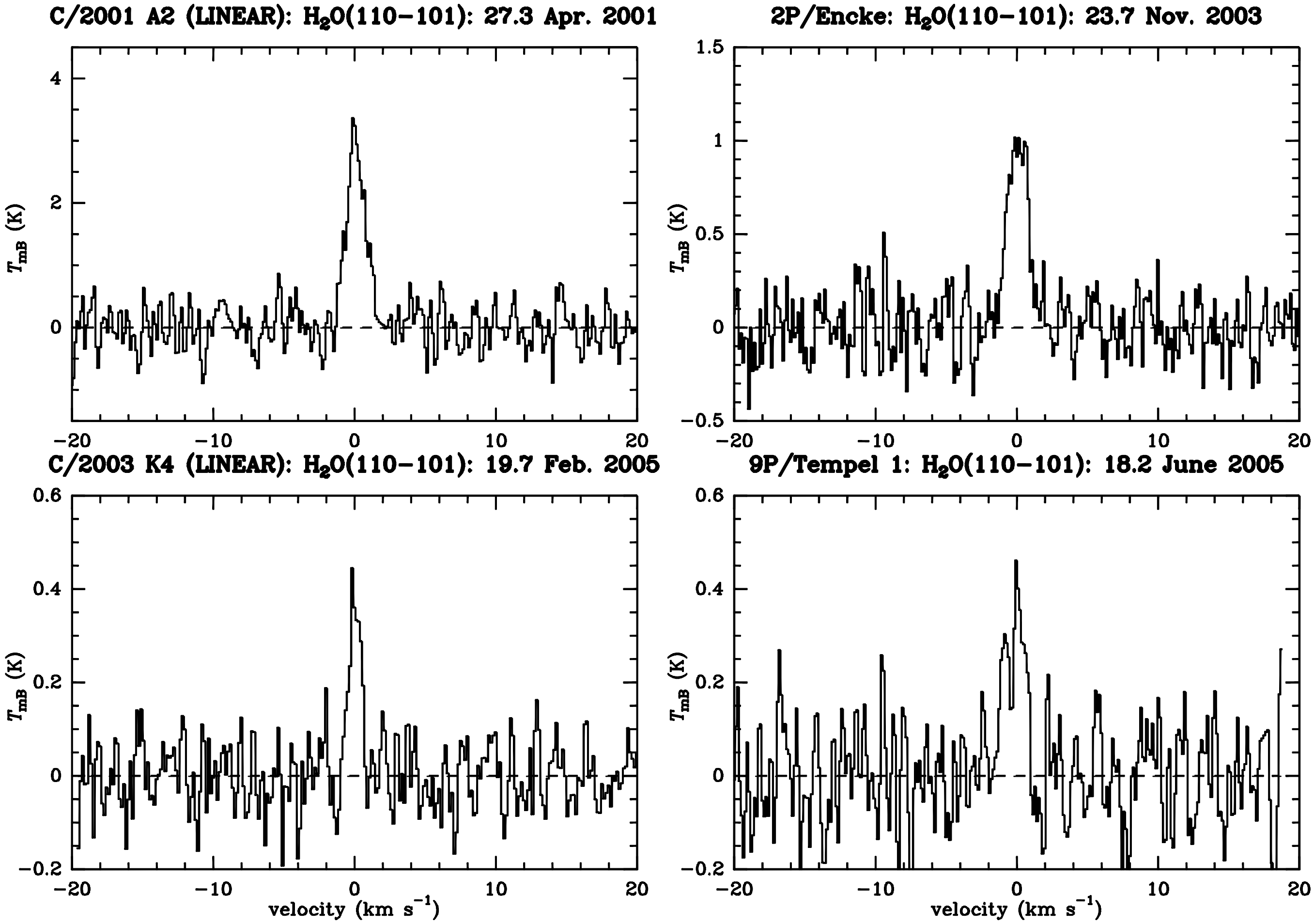

Figure 1: Sample of observations of the 556.9 GHz H_2O line with Odin: C/2001 A2 (LINEAR) on 27 April 2001 (first observation, mean pointing offset is 39"), 2P/Encke on 23 November 2003 (average of centred and offset positions up to 1.5': mean offset is 51"), C/2003 K4 (LINEAR) on 19 February 2005 (most distant detection, r_h=2.23 AU, centred position) and 9P/Tempel 1 on 18 June 2005 (first observation of the Deep Impact campaign, average of centre and 1' offset positions: mean offset is 46"). The vertical scale is the intensity in main beam brightness temperature and the horizontal scale is the Doppler velocity with respect to the comet nucleus.

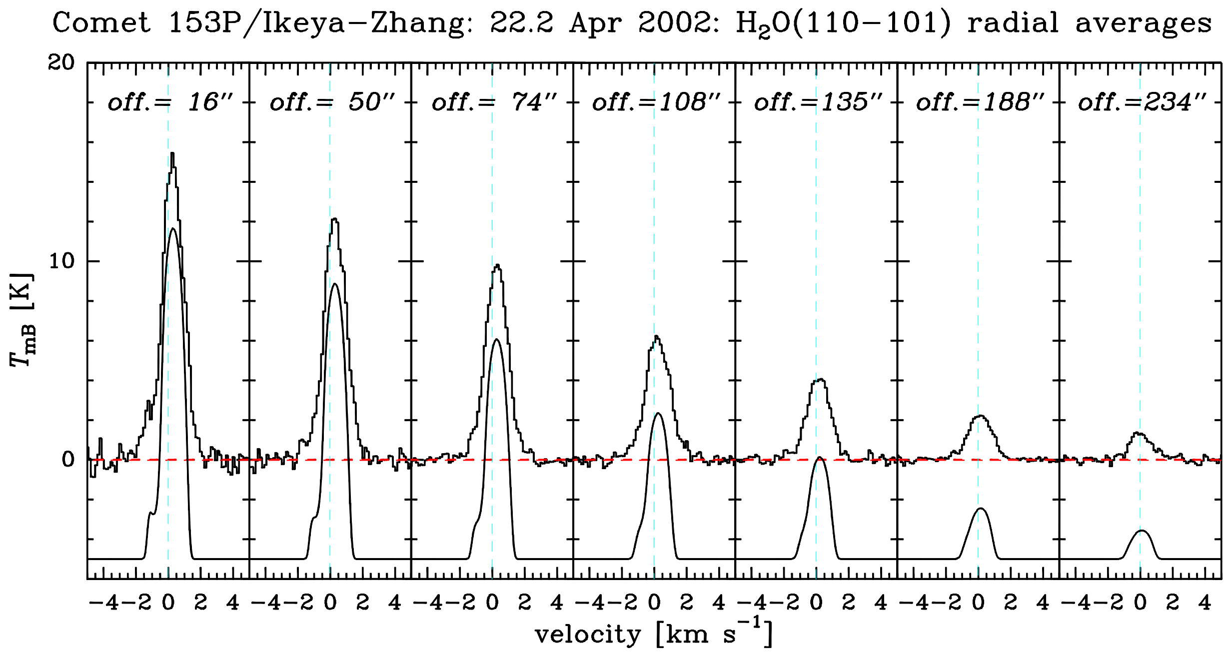

Figure 2: Observed (top) and simulated (shifted down by 5 K) H_2O line profiles versus radial distance from the nucleus in the coma of comet 153P/Ikeya-Zhang. Data are extracted from the radial averages of the map obtained on 22 April 2002. The differences of the line areas and Doppler shifts between predicted and observed values are below 3-σ.

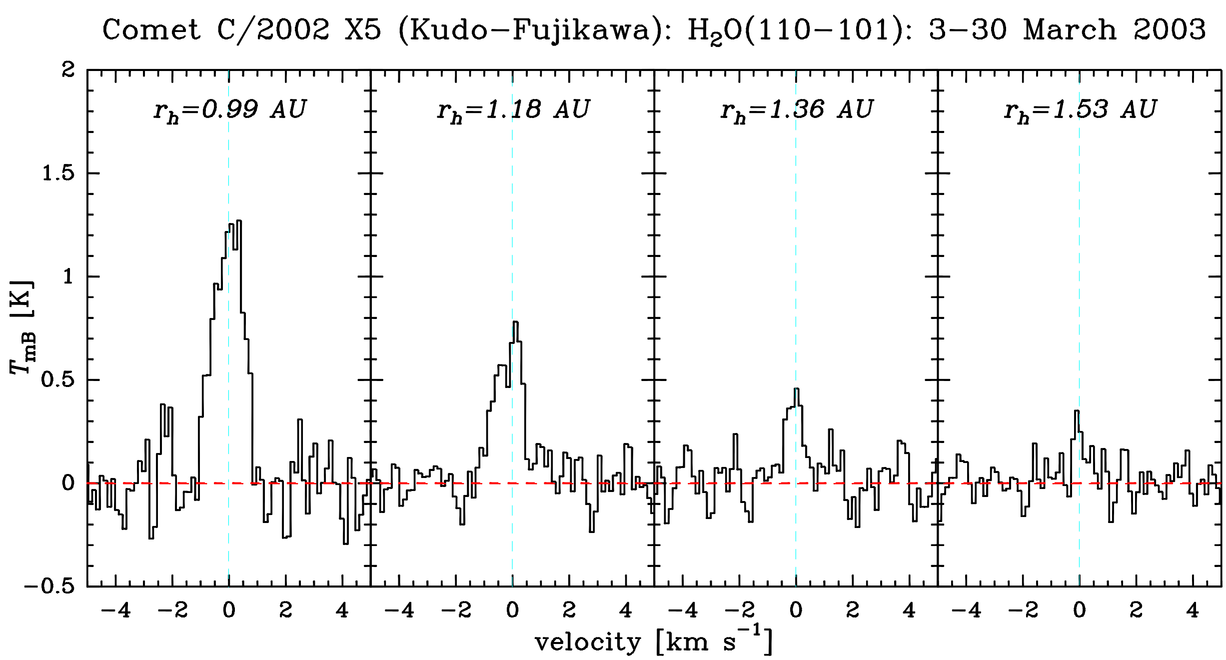

Figure 3: $H_2O(1_{10} - 1_{01})$ line at 556.9 GHz observed by Odin in comet C/2002 X5 (Kudo-Fujikawa) on 3, 12, 21 and 30 March 2003. Note the decrease of the line intensity and width as the comet is moving away from the Sun and decreasing in activity.

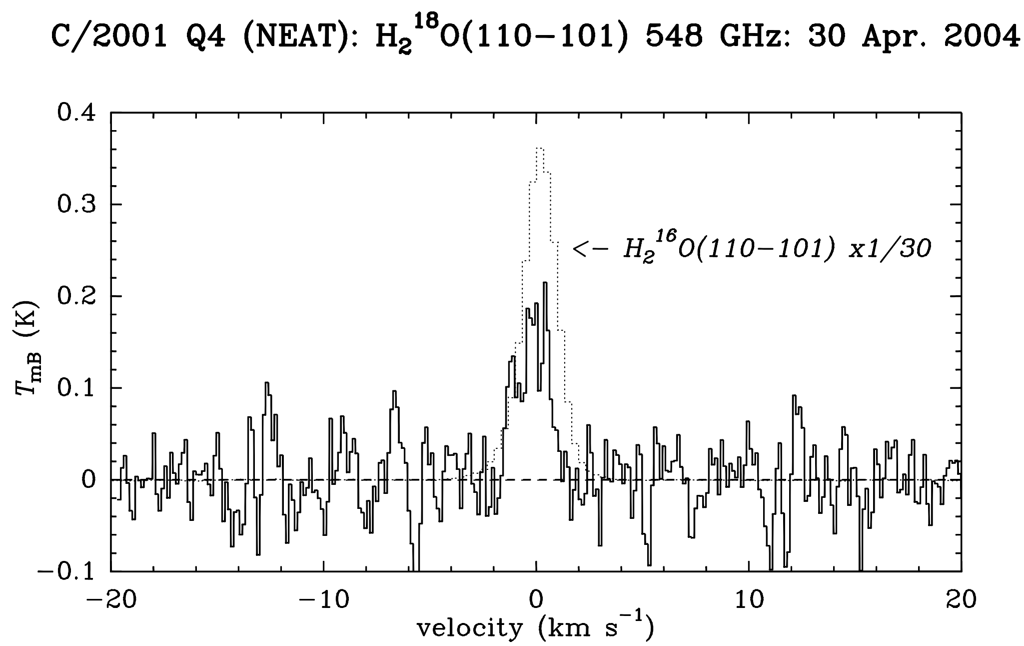

Figure 4: The 547.7 GHz $H_2^{18}O$ line observed with Odin and the AC2 autocorrelator in comet C/2001 Q4 (NEAT): average of 26.7 April to 2.9 May data. Dotted line: the 556.9 GHz $H_2^{16}O$ line observed simultaneously with the acousto optical spectrometer, scaled down by a factor of 30.

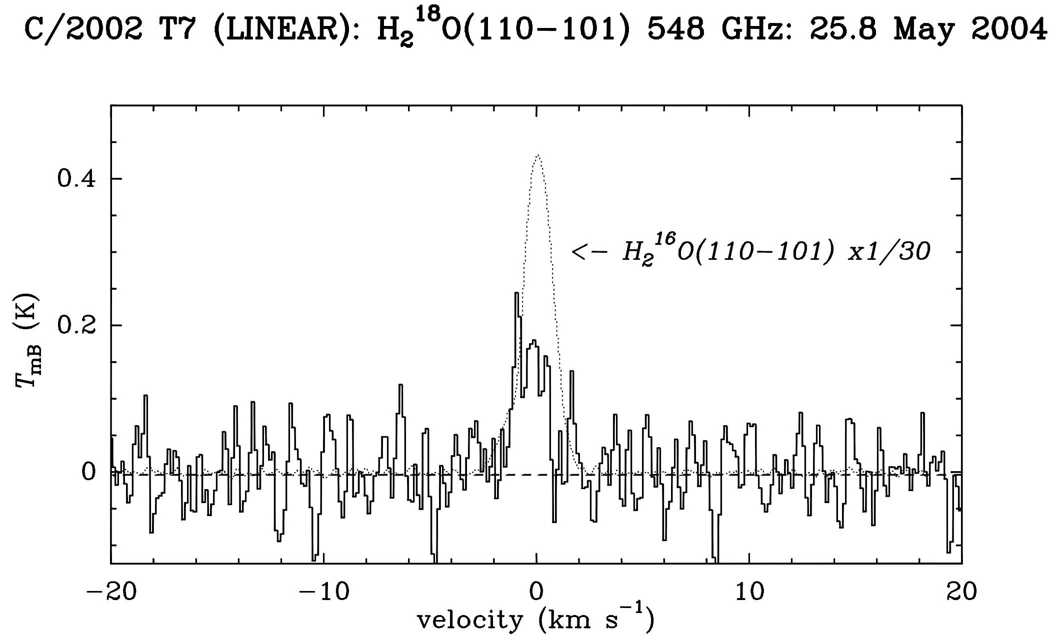

Figure 5: The 547.7 GHz $H_2^{18}O$ line observed with Odin and the AC2 autocorrelator in comet C/2002 T7 (LINEAR): average of 24.1 to 27.5 May data. Dotted line: the 556.9 GHz $H_2^{16}O$ line observed during the same time interval, scaled down by a factor of 30.

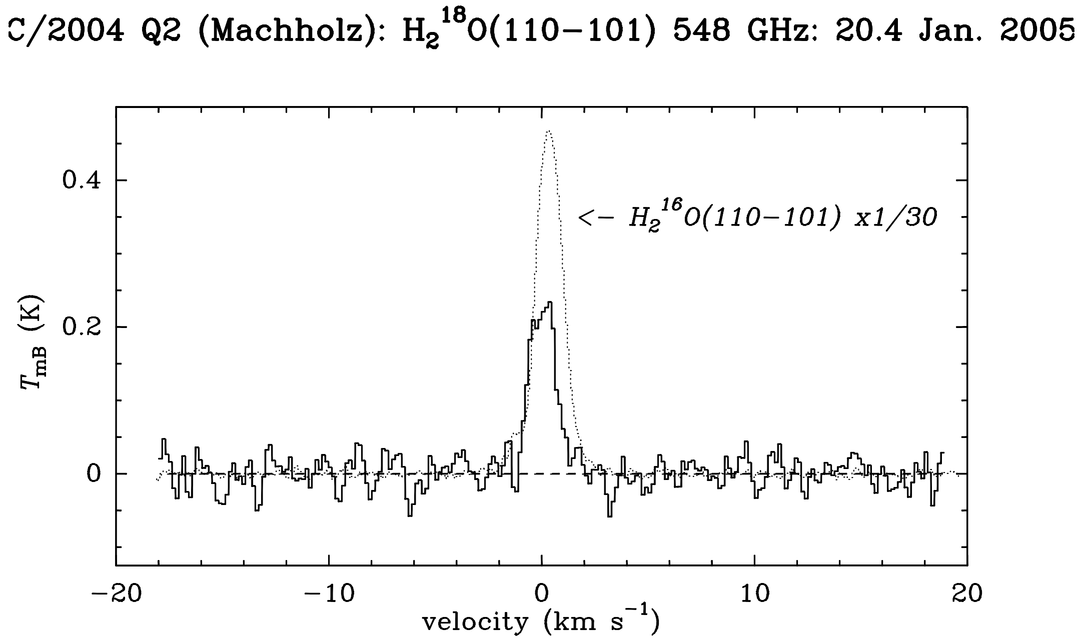

Figure 6: The 547.7 GHz $H_2^{18}O$ line observed with Odin and both autocorrelators in comet C/2004 Q2 (Machholz): average of 17.8 to 23.8 January data. Dotted line: the 556.9 GHz $H_2^{16}O$ line observed during similar time interval (17.8–21.8 Jan.), scaled down by a factor of 30.

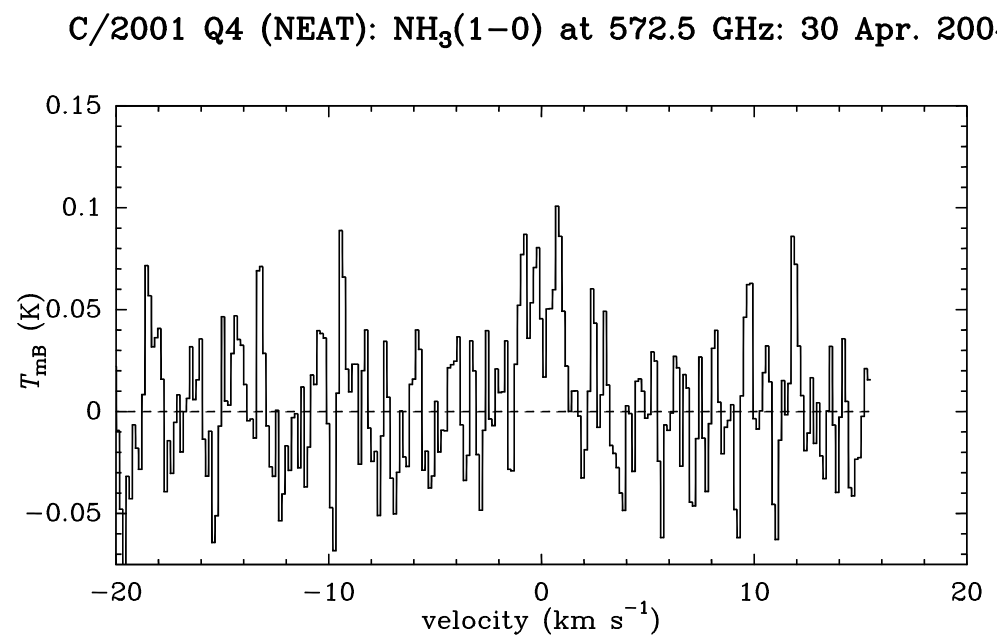

Figure 7: The 572.5 GHz NH_3 line observed with Odin and the AC1 autocorrelator in comet C/2001 Q4 (NEAT): average of 26.7 April to 2.9 May data. $H_2^{16}O$ and $H_2^{18}O$ observations were conducted in parallel.

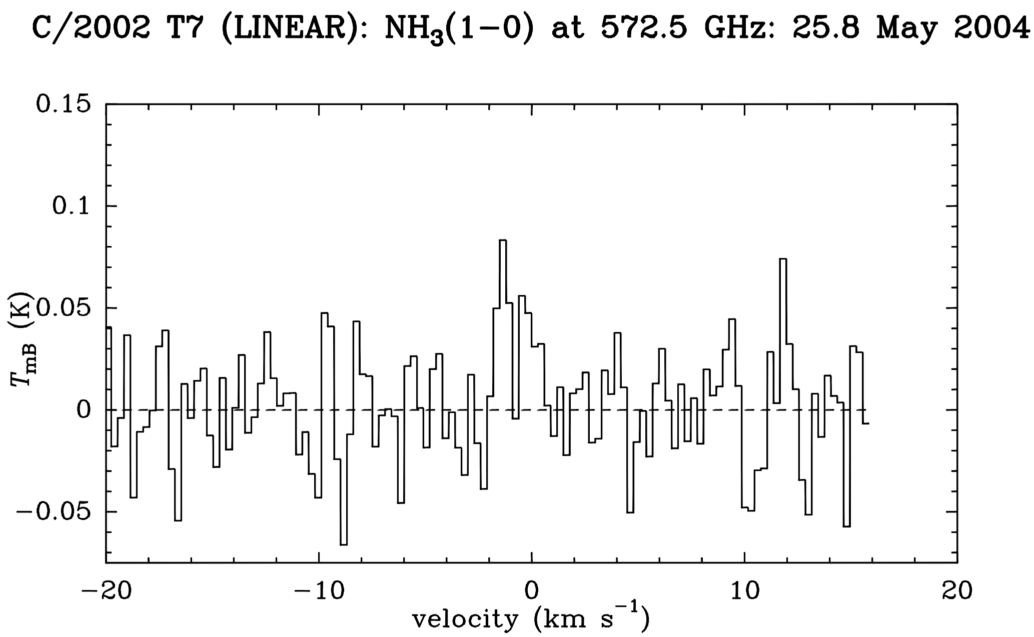

Figure 8: The 572.5 GHz NH_3 line observed with Odin and the AC1 autocorrelator in comet C/2002 T7 (LINEAR): average of 24.1 to 27.5 May data. Due to the lack of terrestrial line at this frequency, the velocity scale has yet to be calibrated and can be still off by up to 0.5 km/s. But as for C/2001 Q4 observations (Fig. 4, 7), comparison to $H_2^{18}O$ line observed simultaneously (Fig. 5) suggests that the blue-shift of the line is real.

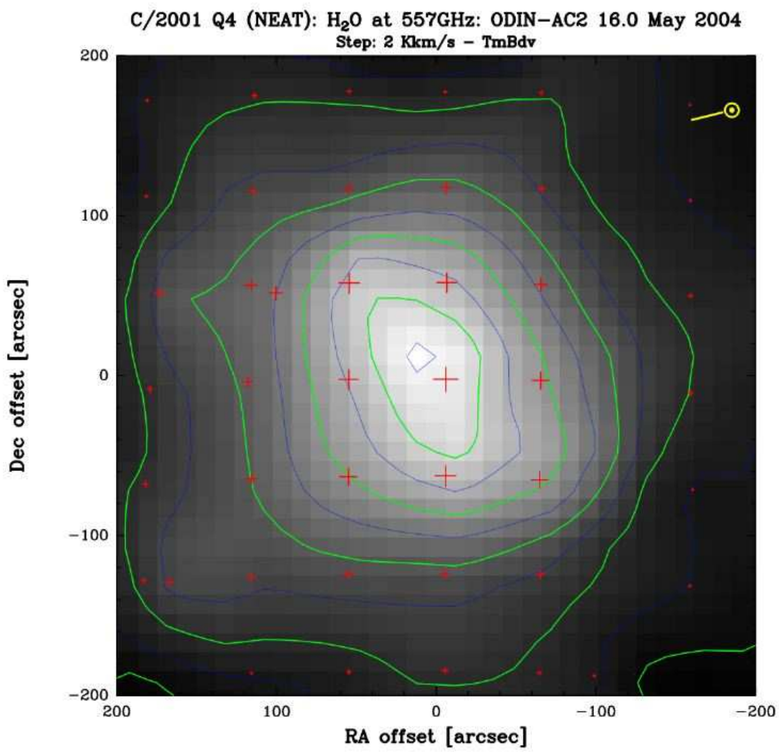

Figure 9: Gray scale and contours of the integrated intensity of the 556.9 GHz water line mapped, with a 7×7 point grid at 1' spacing, in comet C/2001 Q4 (NEAT) on 16 May 2004. Crosses correspond to actual measurements, with size proportional to line integrated intensity. The peak intensity is 19 K km s^{-1} and contours are drawn by steps of 2 K km s^{-1}. Some extension perpendicular to the Solar direction indicated in the upper right seems to be present. The phase angle was 84° during the observations.

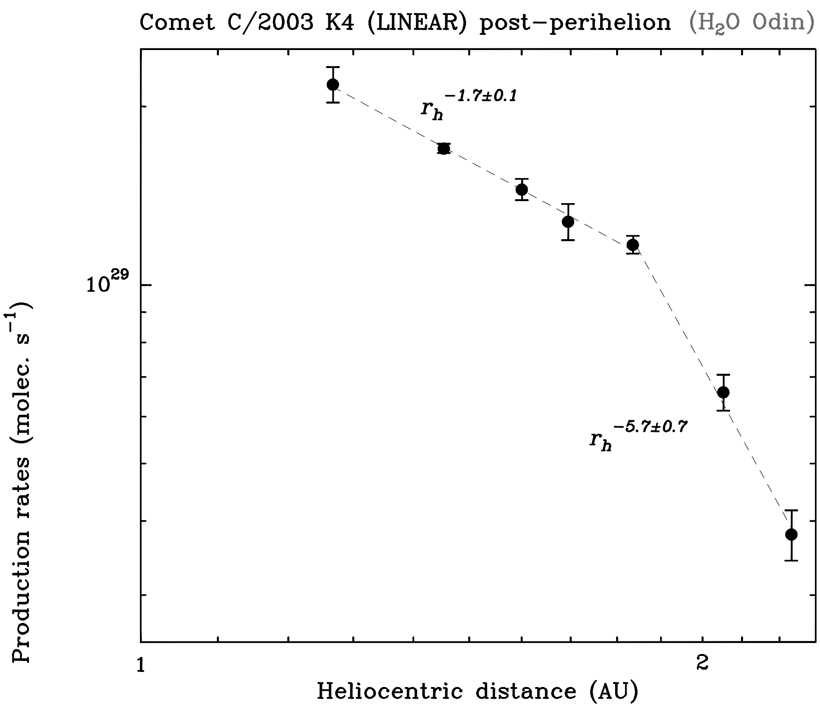

Figure 10: The evolution of the water outgassing rate of comet C/2003 K4 (LINEAR) with heliocentric distance when the comet receded from the Sun between Nov. 2004 and Feb. 2005. Note the change of slope around 1.9 AU.